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ENVIRONMENT INSENSITIVE MOBILE TERMINAL ANTENNAS

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Abstract

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The main emphasis of this licentiate thesis is in investigating and developing novel mobile terminal antennas having optimal performance in different operating environments. The mobile terminal antenna should work efficiently regardless whether the user is in the vicinity of the antenna or not. In addition, the electromagnetic radiation absorbed by the user should be as small as possible.

First, the effect of the user's hand on the antenna performance is studied, and a novel antenna shielding method to decrease the effect of the hand and head is developed. It is shown that the shielding structure can decrease specific absorption rate (SAR) in the head by 81% at 900 MHz and the corresponding improvement in radiation efficiency is 2.8 dB compared to the tradiational antenna. Secondly, the feasibility of balanced antenna structures in mobile terminals is investigated. The balanced antennas can be used in applications requiring high electromagnetic isolation between multiple antenna elements. It is also shown that in some cases the electromagnetic interaction between the antenna and the user can be decreased by using a balanced antenna instead of an unbalanced one. However, the use of balanced antennas is typically limited to higher UHF frequencies, over 2 GHz. Finally, a novel method to control the electromagnetic near fields of a mobile terminal by using wavetraps is introduced. Wavetraps can be used to significantly decrease the electric and magnetic fields at the open end of the chassis of the terminal and thus improve the hearing-aid combitibility.

Keywords: balanced antenna, capacitive coupling element, hearing-aid compatibility, mobile antennas, specific absorption rate, user effect

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Tämän lisensiaatintutkimuksen pääpaino on tutkia ja kehittää uudenlaisia matkapuhelinantenneja, joilla on mahdollisimman hyvä suorituskyky vaihtelevissa käyttöolosuhteissa. Matkapuhelinantennin tulee toimia tehokkaasti riippumatta siitä onko käyttäjä matkapuhelinantennin läheisyydessä vai ei. Lisäksi käyttäjään kohdistuvan sähkömagneettinen säteilyn tulisi olla mahdollisimman pieni.

Aluksi työssä tutkitaan käyttäjän käden vaikutusta antennin suorituskykyyn sekä esitetään uudentyyppinen antennirakenne, jolla on voitu vähentää käden ja pään vaikutusta antennin suorituskykyyn. Tällä rakenteella päähän kohdistuvaa ominaisabsorptiota (SAR) voidaan pienentää 81 % sekä parantaa säteilyhyötysuhdetta 2.8 dB 900 MHz:n taajuudella verrattuna perinteiseen antennirakenteeseen. Lisäksi työssä on tutkittu balansoitujen antennien soveltuvuutta matkapuhelimiin. Balansoituja antenneja voidaan käyttää kohteissa, jotka tarvitsevat suurta antennien välistä sähkömagneettista isolaatiota. Lisäksi joissain tapauksisssa balansoituja antenneja voidaan käyttää pienentämään antennin ja käyttäjän välistä vuorovaikutusta. Balansoitujen antennien käyttö rajoittuu kuitenkin korkeahkoille, yli 2 GHz taajuuksille kaistanleveysrajoitusten takia. Lopuksi työssä esitetään uudentyyppinen aaltoloukkuihin perustuva rakenne, jolla voidaan pienentää merkittävästi sähkö- ja magneettikenttiä puhelimen rungon päädyssä ja siten parantaa kuulolaiteyhteensopivuutta.

Avainsanat: balansoitu antenni, kapasitiivinen kytkentäelementti, kuulolaiteyhteensopivuus, käyttäjän vaikutus, matkapuhelinantennit, ominaisabsorptionopeus

Preface

The research work of this licentiate's thesis has been carried out during 2009-2012 at the Department of Radio Science and Engineering in Aalto University School of Electrical Engineering. The work has been partly financed by the Finnish Technology Agency (TEKES), the Academy of Finland through the Centre of Excellence program (SMARAD), and Finnish telecommunications industry.

I would like to thank Professor Pertti Vainikainen for giving me the opportunity to work on this challenging and interesting subject. I highly appreciate his support and our thoughtful discussions.

My first instructor Dr. Outi Kivekäs deserves my deepest gratitude for her excellent guidance given at the beginning of my postgraduate studies. I also wish to express my sincere gratitude to my second instructor and workmate, Dr. Jari Holopainen, for his willingness to share his expertise on the small antennas.

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Espoo, May 4, 2012

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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I J. Ilvonen, O.Kivekäs, J. Holopainen, R. Valkonen, K. Rasilainen, and P. Vainikainen, "Mobile terminal antenna performance with the user's hand: effect of antenna dimensioning and location," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 772-775, 2011.

II J. Ilvonen, R. Valkonen, O. Kivekäs, P. Li, and P. Vainikainen, "Antenna shielding method reducing the interaction between user and mobile terminal antenna," *Electronics Letters*, vol. 47,issue 16, pp. 896 - 897, 2011.

III J. Ilvonen, R. Valkonen, J. Holopainen, O. Kivekäs, and P. Vainikainen, "Reducing the interaction between user and mobile terminal antenna based on antenna shielding," In *6th European Conference on Antennas and Propagation (EuCAP 2012)*, Prague, Czech Republic, pp. 1-5, 26-30 March 2012.

IV J. Ilvonen, J. Holopainen, O. Kivekäs, R. Valkonen, C. Icheln, and P. Vainikainen, "Balanced antenna structures of mobile terminals," In *4th European Conference on Antennas and Propagation (EuCAP 2010)*, Barcelona, Spain, pp. 1-5, 12-16 April 2010.

V J. Ilvonen, O. Kivekäs, A.A.H Azremi, J. Holopainen, R. Valkonen, and P. Vainikainen, "Isolation improvement method for mobile terminal antennas at lower UHF-band," In *5th European Conference on Antennas and Propagation (EuCAP 2011)*, Rome, Italy, pp. 1307-1311, 11-15 April 2011.

VI J. Holopainen, J. Ilvonen, O. Kivekäs, R. Valkonen, C. Icheln, and P. Vainikainen, "Near-field control of handset antennas based on inverted top wavetraps: focus on hearing-aid compatibility," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 592-595, 2009.

Author's Contribution

Publication I: "Mobile terminal antenna performance with the user's hand: effect of antenna dimensioning and location"

The work was mainly done by the author. The author had the main responsibility for developing the idea. The author carried out the simulations and was responsible for writing the publication. Dr. Outi Kivekäs participated in the development of the idea and in the writing of the paper. Mr. Kimmo Rasilainen helped with the simulations. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication II: "Antenna shielding method reducing the interaction between user and mobile terminal antenna"

The antenna shielding idea is based on the joint idea of this author and Mr. Risto Valkonen. The author had a leading role in developing the idea, writing the publication and performing the simulations. Mr. Risto Valkonen participated in the writing of the paper and the analysis of the results. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication III: "Reducing the interaction between user and mobile terminal antenna based on antenna shielding"

The work was mainly done by the author. The idea for the antenna shielding is presented in [II]. The author performed the simulations, design and fabrication of the prototype and measurements. Dr. Jari Holopainen instructed and Prof. Pertti Vainikainen supervised the work.

Publication IV: "Balanced antenna structures of mobile terminals"

The work was mainly done by the author. The author had the main responsibility for developing the idea. The author carried out the simulations and was responsible for writing the publication. Dr. Jari Holopainen participated in the development of the idea and worked as the instructor. Prof. Pertti Vainikainen supervised the work.

Publication V: "Isolation improvement method for mobile terminal antennas at lower UHF-band"

The work was mainly done by the author. The author had the main responsibility for developing the idea. The author carried out the simulations and was responsible for writing the publication. Mr. Azremi Abdullah Al-Hadi participated in analysing the results. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication VI: "Near-field control of handset antennas based on inverted top wavetraps: focus on hearing-aid compatibility"

This is the result of collaborative work. The idea was found by the author together with Dr. Jari Holopainen. Dr. Jari Holopainen had a leading role writing the paper. The author carried out the simulations and participated in analysing the results. Prof. Pertti Vainikainen supervised the work.

List of Abbreviations

ANSI	American National Standards Institute
CAD	Computer Aided Design
CCE	Capacitive Coupling Element
CDMA	Code Division Multiple Access
E-GSM	Extended GSM
EMC	Electromagnetic Compatibility
FDTD	Finite-Difference Time-Domain
FET	Field-Effect Transistor
GaAs	Gallium Arsenide
GSM	Global System of Mobile Communications
HAC	Hearing-Aid Compatibility
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IFA	Inverted-F Antenna
MEMS	Microelectromechanical Systems
MIMO	Multiple-Input and Multiple-Output
MoM	Method of Moments
MRC	Maximal Ratio Combining
NFC	Near Field Communication
LTE	Long Term Evolution (advanced 3G technology)
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
PIFA	Planar Inverted-F Antenna
RAMS	Rapid Antenna Measurement System
RDF	Radio Direction Finding
RF	Radio Frequency
RMS	Root Mean Square
SAM	Specific Anthropomorphic Mannequin
SAR	Specific Absorption Rate
SNR	Signal-to-Noise Ratio

TDMA	Time Division Multiple Access
UHF	Ultra High Frequency band (300 - 3000 MHz)
UMTS	Universal Mobile Telephone System
VNA	Vector Network Analyser
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

List of Symbols

a	radius of a sphere
C	capacitance / capacitor
DG	diversity gain
E	electrical field strength
EDG	effective diversity gain
$e_{\mathrm{rad,i}}$	total embedded radiation efficiency
f_{r}	resonant frequency
H	magnetic field strength
J	electric current density
$\jmath$	imaginary unit
k_0	wave number in free space
L	inductance
MEG	mean effective gain
m_h	mean elevation angle of horizontally polarised wave distribution
m_v	mean elevation angle of vertically polarised wave distribution
P_{rad}	radiated power
Q	quality factor
Q_0	unloaded quality factor
Q_{rad}	radiation quality factor
Q_{Z}	calculated quality factor (from input impedance)
R	resistance / resistor
S_{11}	scattering parameter
SAR	specific absorption rate
XPR	cross-polarisation ratio
Z_0	characteristic impedance of a feed line
ϵ_0	permittivity in free space
ϵ_{r}	relative permittivity
η	efficiency
η_{m}	matching efficiency

η_{rad}	radiation efficiency
η_{tot}	total efficiency
λ	wavelength
λ_0	wavelength in free space
μ	permeability
ω_{r}	angular resonant frequency
ρ_{d}	density of tissue
ρ_{e}	envelope correlation
σ	conductivity
σ_{eff}	effective conductivity
σ_{h}	standard deviation of horizontally polarised wave distribution
σ_{v}	standard deviation of vertically polarised wave distribution

1. Introduction

1.1 Background

In the early 2000s, the main trends in mobile terminal antenna development were miniaturizing the internal antenna structure and implementation of multi-frequency functionality. About at the same time, the standardized safety limits on the radio frequency exposure (SAR, specific absorption rate) were introduced [1]. It was also observed that in order to have robust antenna performance, the effect of the user cannot be neglected, though the antennas were and still are often designed to have optimal performance in free space, without a user. Currently the tendency is towards larger devices mainly due to a changed way to use mobile terminals; internet browsing, near field communication (NFC), and positioning services have increasing popularity. This will increase demands towards an increasing number of radio systems introduced in the terminal (see Fig. 1.1), each requiring antenna(s) [2]. Furthermore, the number of antennas in mobile terminals will increase due to the increasing use of multiple-input and multiple-output (MIMO) techniques, while the space available for the antennas is decreasing. This will cause, for instance, problems with electromagnetic isolation between closely located antennas. In addition to the increased number of antennas and the isolation issues, different ways to hold a mobile terminal and different hand grips have to be taken into account in order to ensure efficient antenna operation. Thus, there are lots of new challenges and increased demands set for mobile terminal antennas.

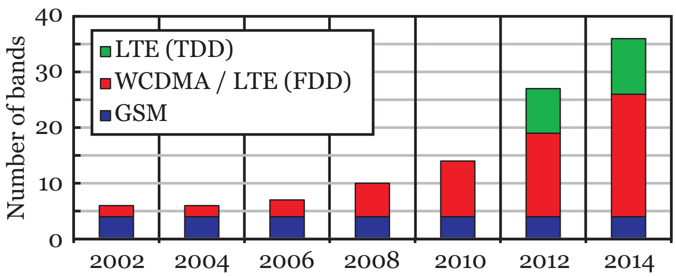


Fig. 1.1. Evolution of cellular RF bands [3].

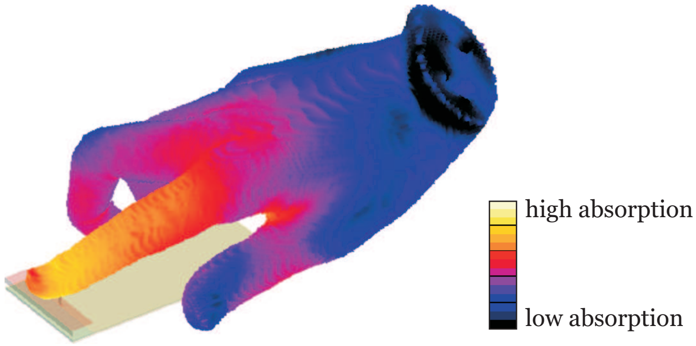


Fig. 1.2. Distribution of absorption losses in hand.

The most demanding task in mobile terminal antenna design is to create small enough and realisable antennas which operate at multiple systems, have sufficient operational bandwidth, high radiation efficiency, and still can fulfil the SAR and hearing-aid compatibility (HAC) requirements. Additionally, the antennas should work well in the vicinity of the user (see Fig. 1.2). Unfortunately, it is not possible to improve all the antenna properties at the same time. Typically, the improvement of one property will deteriorate the others [I, 4]. Hence, it is demanding to develop an antenna element that will work well in all environments and devices.

1.2 Objectives of the work

The general objective of this thesis is to investigate and develop environment insensitive mobile terminal antennas which are tolerant to external disturbances, such as the user's body. Another goal is to reduce the power absorbed by the user, meaning that the electromagnetic radiation emitted by the mobile terminal is directed away from the user. Hence, some effort was put on the investigation of SAR and HAC.

1.3 Research methods

A number of researchers have used electromagnetic (EM) simulators for studying the effect of the user with good reliability regarding comparisons with measurements [5–9]. Hence, a major part of the results and conclusions presented in this thesis are based on simulated results. In this thesis, the simulations were performed by using three different types of commercial EM and circuit simulators: *a*) an FDTD-based EM-simulator SEMCAD X by SPEAG [10], *b*) a Method of Moments (MoM)-based simulator IE3D by Mentor Graphics [11], and *c*) a circuit simulator AWR Design Environment [12]. The simulation studies presented in [I-VI] were performed using

SEMCAD X. The matching losses with and without the user [III] were simulated by using SEMCAD X and AWR Design Environment. The free-space simulations performed in [IV] were done with IE3D.

1.4 Contents of the thesis

This thesis consists of a summary and six publications [I-VI] . This summary is organized as follows. In Chapter 2, different challenges of mobile terminal antennas in the vicinity of the user are discussed [I]. Furthermore, different methods to reduce the electromagnetic interaction between the user and a mobile terminal antenna are studied in Chapter 3 [II, III, IV, V, VI]. Chapter 4 contains the conclusions and topics for future research.

2. Mobile terminal antennas in the vicinity of a user

In today's mobile terminals with internal antenna elements the chassis or PCB of the mobile terminal is used as a radiator and the antenna element creates the antenna resonance (possibly together with a matching circuit) for the impedance matching to the transceiver and inherently couples currents to the chassis. Especially at the lower UHF frequencies, below 1 GHz, a significant portion of the power is radiated by the chassis [13]. Therefore, the size of the terminal on which the antenna is located and the location of the antenna relative to the chassis have a remarkable effect on the mobile terminal antenna performance. In addition, the effect of the user on the operation of the mobile terminal antenna has to be taken into account from two different perspectives. The human body can affect the operation of the antenna and vice versa. First in Section 2.1, the effect of the user on the impedance matching and radiation efficiency is discussed. In Section 2.2, beneficial approaches and general guidelines for antenna designs with reduced effect of the user's hand are given [I]. Finally in Section 2.3, the main disadvantages of the electromagnetic radiation of the mobile terminals are discussed.

The capacitive coupling element (CCE) based antenna structures introduced in [I, 14] (see Fig. 2.1) are mostly used in this thesis to investigate and demonstrate the interaction between the antenna and the user. The non-self-resonant CCE antennas are especially suitable for this kind of study due to the following reasons [15, 16]: *a*) the CCE can be tuned with an external matching circuitry to have a resonance at almost any frequency, *b*) the geometry of the antenna element can be very simple, *c*) the geometry of the antenna element is not dependent on the operating frequency and thus the investigation of the hand losses is straightforward, and *d*) the contribution of the dielectric loading caused by the user is fairly evenly distributed over the CCE due to the lack of fine geometrical details. In addition to the above-mentioned features, the CCE antennas can be used to analyse the properties of the chassis wavemodes with a user. This is because the CCE is inherently non-self-resonant and thus the CCE can be seen as a 'transparent' block between the matching circuit and the chassis (see Fig. 2.2) [17, 18]. Furthermore, the analysis can be performed without a matching circuit for the CCE since the user is not affecting the matching circuit [8].

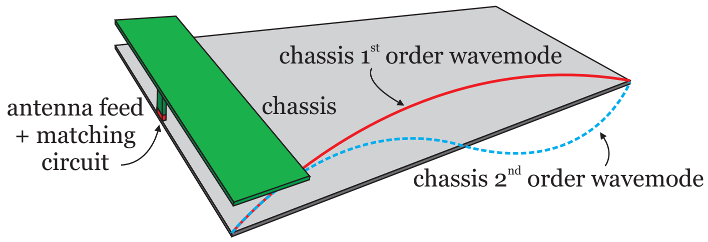


Fig. 2.1. Capacitive coupling element (CCE) mounted on the chassis, with two principal current distributions of the lowest order wavemodes of the chassis.

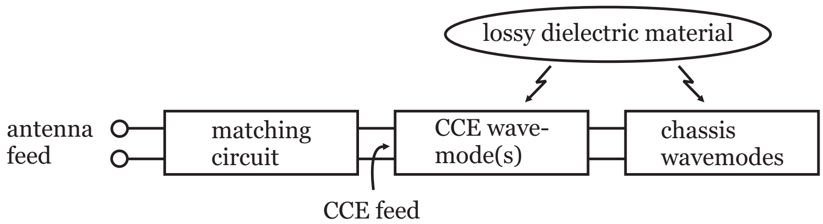


Fig. 2.2. Circuit blocks of the equivalent circuit model with lossy dielectric loading (such as a user) [18].

2.1 Effect of the user on impedance matching and radiation efficiency

Typically, the predetermined location and available volume of an antenna in a mobile device set strict limitations for a mobile antenna designer [4]. An additional challenge is the inevitable change of performance when the user is located in the close vicinity (see Fig. 2.3). In most cases, the effect of the user on the performance of the mobile terminal antenna is destructive causing, for instance, the reduction of RF power, input impedance variation, and the change of the radiation pattern [I, IV, 16, 19–23]. Existing broad understanding of the head effect [4, 24–26] as well as the increasing use of data services direct the main concern to studies on the effect of the hand. Small tolerances in the dielectric parameters or geometry of the hand and the head have a small impact on the antenna operation, while the most important factors are the way the mobile phone is held and the relative position of the index finger with respect to the antenna element [27, 28]. The effect of the hand, especially the index finger, has a significant contribution on the antenna performance. When the user holds the mobile terminal firmly in a talking mode, the hand accounts for most of the absorption losses and the index finger (see Fig. 1.2) can be responsible for almost 50% of the total absorbed power while the head is responsible only for 25% of total absorbed power [29]. Furthermore, it is very challenging to design an antenna having a robust performance against statistical variations of different hand grips of the users [27]. In the multi-antenna case, the effect of the hand can degrade the data throughput due to significant mean effective gain (MEG) imbalance between different antenna branches [30]. On the other hand, in a few cases the user's hand

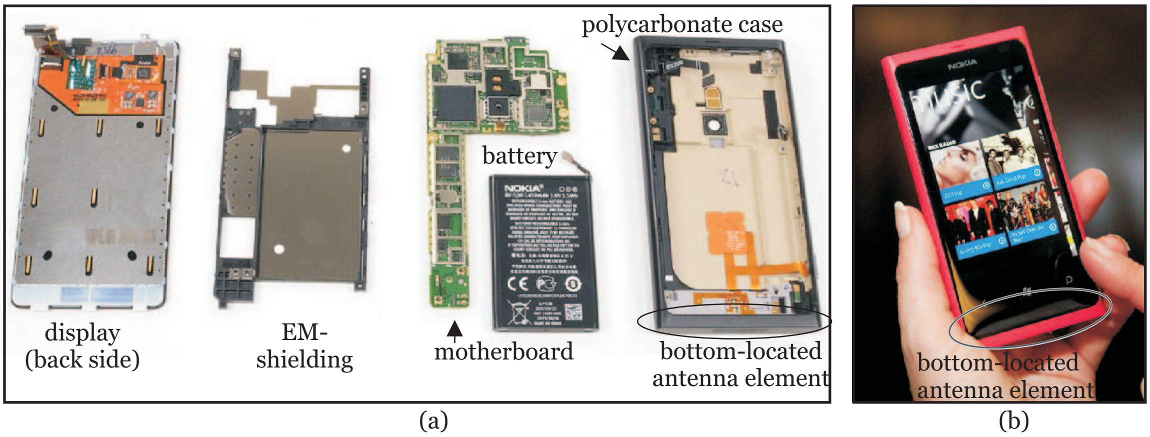


Fig. 2.3. (a) Teardown of the Nokia Lumia 800 [32], and (b) a real use position of the Nokia Lumia 800 [33].

can even improve the performance of lower UHF band antennas. This can occur at lower UHF-frequencies (below 1 GHz), for instance, when the hand is located at the opposite end to the antenna element [8, 17, 31]. The improvement of the total efficiency in this particular case is due to the improved matching efficiency which more than compensates the degration of the radiation efficiency.

The deterioration of the performance of the mobile terminal antenna located close to the human body is due to the fact that the human tissue consists of a lossy dielectric material[1]. The lossy tissue in the reactive near fields of the antenna causes the problems discussed above. The performance degradation can be described as a change of the total antenna efficiency (η_{tot}) between the free space case and with a user. The total antenna efficiency is a product of the radiation efficiency (η_{rad}) and the matching efficiency (η_{m}).

The matching efficiency is defined as the ratio between the power accepted and the power available at the antenna input [34]. Typically, the change of the resonant frequency of the antenna will decrease the η_{m}. The perturbation theory for a filled cavity [35] can be used to approximate the frequency detuning caused by the human body. The theory can be extended to the mobile terminal antennas (with some limitations which will be discussed later) due to the fact that the operation of the mobile terminal antennas is based on the resonant wavemodes of the antenna element and the chassis [13] (see Fig. 2.1). An approximation of the shift of the resonant frequency due to a change in permittivity (ϵ) can be obtained from the general perturbation formula [35]:

[1] $\epsilon_r = \epsilon_r^{'} - \jmath\sigma_{eff}/\omega\epsilon_0$, where $\epsilon_r^{'}$ is the real part of the relative permittivity, ϵ_0 is the vacuum permittivity, and σ_{eff} is the effective conductivity.

$$\frac{\omega - \omega_0}{\omega} = -\frac{\int_V \left[(\epsilon_{r2} - \epsilon_{r1})\epsilon_0 \bar{\mathbf{E}}_2 \cdot \bar{\mathbf{E}}_1^*\right] dV}{\int_V \left[\epsilon_{r1}\epsilon_0 \bar{\mathbf{E}}_2 \cdot \bar{\mathbf{E}}_1^*\right] dV}. \tag{2.1}$$

The subscripts 1 and 2 refer to the cases without and with a user, respectively. The equation states that dielectric material (e.g., hand having $\epsilon_r^{'}$ = 36.2 at 900 MHz) located within the reactive near fields will decrease the resonance frequency of the antenna, causing typically deteriorated matching efficiency (η_{m}). However, this is valid only for a single wavemode case and thus cannot be directly extended to the mobile terminal antennas. The mobile terminal antenna is a combination of antenna element(s) and a chassis and thus consists of several coupled wavemodes. Hence, some specific cases can be found where the resonant frequency of the antenna structure can increase due to the dielectric loading [17].

The radiation efficiency is defined as the ratio of the power radiated and the power accepted by the antenna [34]. It means that the lossy dielectric material (tissue) close to the antenna decreases the η_{rad}. The loss power in the dielectric is

$$P_{loss} = \frac{1}{2}\int_V \mathbf{J} \cdot \mathbf{E}^* dV = \frac{\omega\varepsilon_r^{''}\varepsilon_0}{2}\int_V |\mathrm{E}|^2 \, dV. \tag{2.2}$$

Hence, the absorption loss of the dielectric material is dependent on the electric field strength (E) in the tissue.

The quality factor (Q) of a small antenna can be used to approximate the radiation efficiency of the antenna with a user. The Q can be calculated from the frequency derivative of the unmatched input impedance of the antenna by using the expression[2] introduced in [36]. The calculated quality factor (Q_Z) takes into account the effect of the antenna element and the finite ground plane (effective Q, $Q_{0,eff}$). When the hand is included, its effect is also contained in Q_Z

$$\frac{1}{Q_Z} = \frac{1}{Q_{0,eff}} + \frac{1}{Q_{hand\,losses}}. \tag{2.3}$$

$Q_{0,eff}$ can be further divided into the quality factor of the antenna element ($Q_{0,CCE}$) and quality factor of the chassis ($Q_{0,chassis}$). There exists a following relation between the η_{rad} and the Q of the antenna

$$\eta_{\mathrm{rad}} = \frac{Q_Z}{Q_{0,eff}}. \tag{2.4}$$

[2]The equation is valid for electrically small antennas ($k_0 a < 1$, where k_0 is the wave number in free space and a is the radius of a sphere enclosing an antenna). If the equation is used for larger antennas ($k_0 a > 1$), the proper function of the equation needs to be verified (e.g., an antenna has to exhibit a single impedance resonance within its defined operating bandwidth).

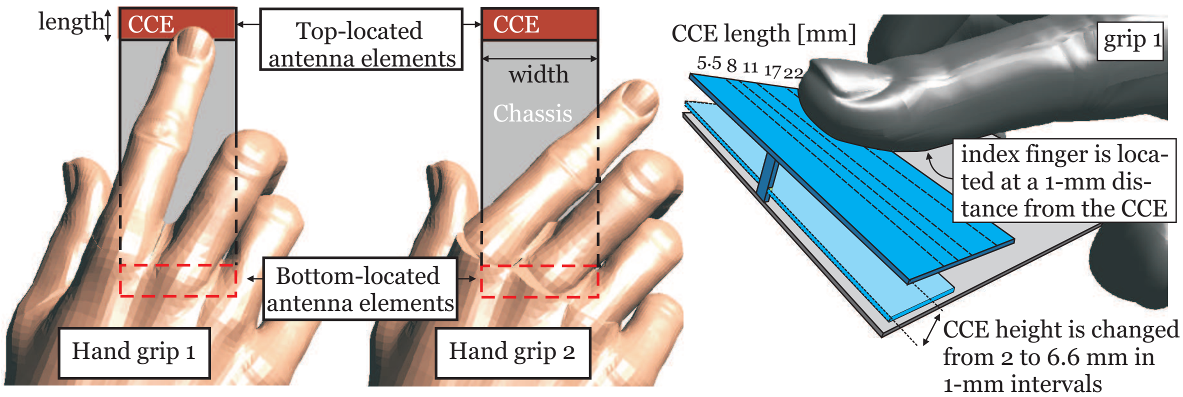
In free space (no losses), we get the value for the $Q_{0,eff}$ as η_{rad} = 1. If we approximate that the $Q_{0,eff}$ = $Q_{1,eff}$ in free space and with the hand, respectively, it is possible to calculate the η_{rad} directly from the antenna input impedance. For instance in [I], the absorption losses of the hand were possible to estimate at 900 MHz with a good accuracy by using the Q_Z. By contrast, at 2000 MHz the Q-based η_{rad} (2.4) underestimates the effect of the hand. The explanation for this might be that a part of the hand is out from the reactive near field of the main resonator, meaning that the hand is causing shadowing, and hence the prediction cannot be made reliably from the input impedance. Another reason for the wrong prediction at higher frequencies is discussed in [I]. The main problem seems to be that at higher frequencies the current distribution of the antenna structure diverges too much between the cases in free space and with the hand and thus the effective quality factor ($Q_{0,eff} \neq Q_{1,eff}$) is approximated in a wrong way leading to the incorrect η_{rad}.

In spite of the fairly well known effect of the user, the commercial mobile terminal antennas are still often designed to have an optimal performance in free space and the performance characteristics are just measured afterwards with a user. An example of this can be found in [37] where the internal antenna element of Nokia's N8 phone model was designed, implemented and measured. The antenna performance in free space is very good but the impact of the user, especially the hand, is significantly deteriorating the radio performance. Nonetheless, the manufacturers of mobile devices are paying increasing attention to the user effect since the network operators will have increasing requirements for maximizing the radiation efficiency of mobile terminal antennas with a user and because a poorly working device will give bad publicity as in the case of the antenna element of Apple's iPhone 4. The matching losses of this antenna increase up to 6.4 dB at GSM850 band when a user holds the device in such a way that the metal antenna is partly shorting out [38]. A promising way to decrease the matching losses by using an adaptive antenna tuner is introduced in [39, 40]. However, this kind of method tends to increase the complexity and power loss of the antenna implementation. An alternative method is to design the matching circuit in such a way that the impedance matching is not deteriorated substantially even if the user's hand is located next to the antenna element [16].

2.2 Antenna performance with the user's hand: effect of antenna dimensioning and location

Different hand grips, hand positions and antenna types have been investigated in many previous publications, for instance, in [IV, 41–46]. However, there are no published results on how small changes in the dimensions and locations of mobile terminal antennas affect the interaction between the antenna and the user's hand. Such results would provide useful knowledge for antenna designers and they could be utilised for designing antennas with a reduced effect of the user.

In [I], this lack of information is reduced by analysing an extensive set of simulation series to demonstrate how the quality factor (Q), resonant frequency detuning (Δf_r) and decrease in radiation efficiency (η_{rad}) due to the user's hand can be traded off with only minor changes in the antenna dimensions or location. As discussed earlier, the CCE antennas are especially suitable for this kind of parametric study and thus those are investigated with different dimensions and locations at 900 and 2000 MHz. The characteristics have been studied with a realistic CAD model of a phantom hand with two different grips. The grip 1, shown in Fig. 2.4 (a), is based on the standardization work [47] and the grip 2 is similar to the grip 1 except for the index finger being located on the chassis edge, see Fig. 2.4 (b).



(a) (b) (c)

Fig. 2.4. Used hand grips. (a) grip1 and (b) grip2. (c) Length and height of the CCE are changed from 5.5 to 22 mm and from 2 to 6.6 mm, respectively. The antenna element is located either in the top or bottom part of the structure.

In Fig. 2.4 (c), the studied lengths and heights of the CCE are shown. The tip of the index finger is always located at a 1 mm distance from the CCE. The main trend seems to be that when decreasing the Q_Z by increasing the CCE height or the CCE area, there is only a minor effect on the η_{rad} (see Fig. 2.5). However, the larger the CCE height or the CCE area is, the larger is the Δf_r resulting in decreased η_{tot} but also in wider impedance bandwidth. For example, when decreasing the height and area of the CCE it is possible to reduce the Δf_r and maintain the η_{rad} at the cost of impedance bandwidth. Instead, when the Q_Z is altered by changing the CCE location (results presented in [I]) along the chassis, a distinct interconnection between the Q_Z, η_{rad} and Δf_r can be shown: a maximum in η_{rad} and a minimum in Δf_r occur when the Q_Z has its maximum.

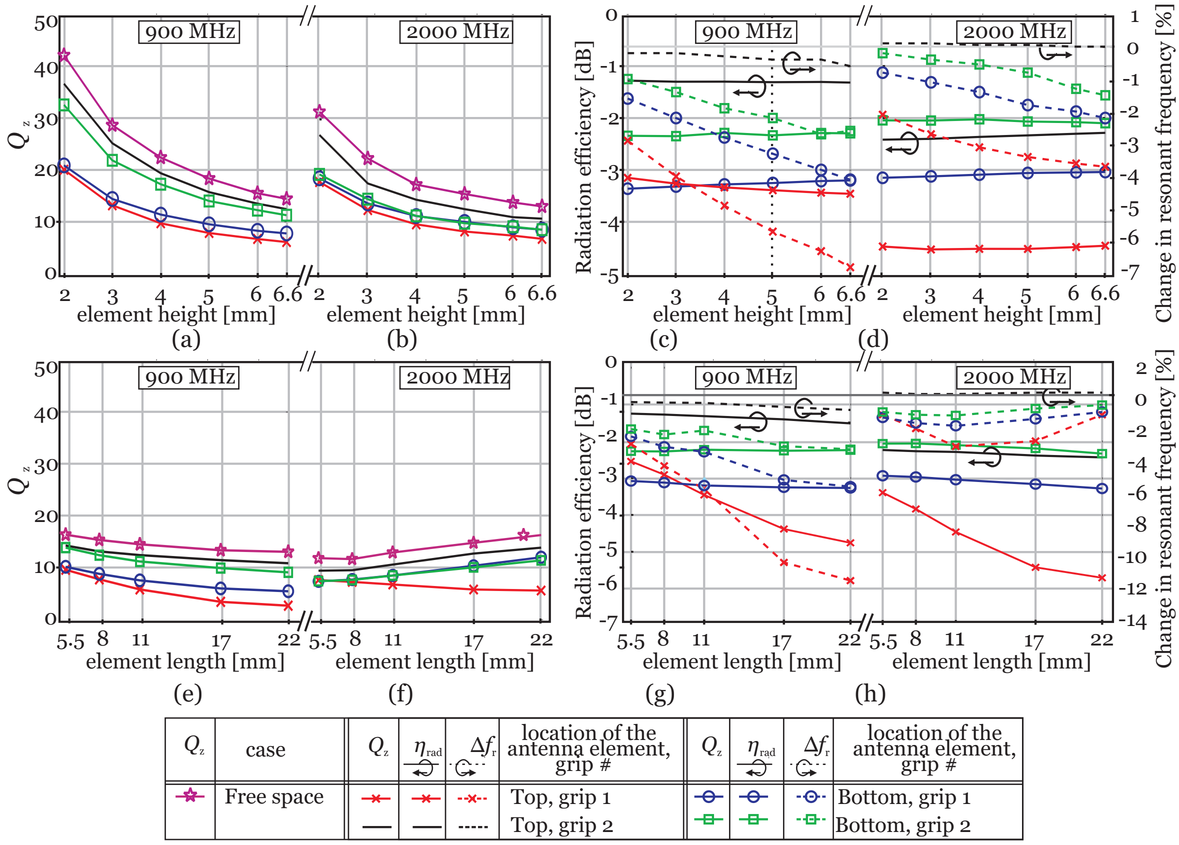
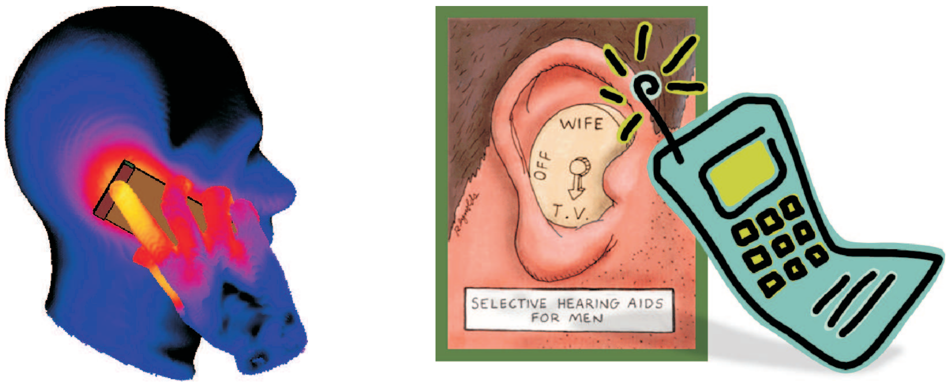


Fig. 2.5. Quality factor, radiation efficiency and change in resonant frequency as a function of CCE height and CCE length at 900 MHz and 2000 MHz.

Typically, the improvement of one property seems to deteriorate the other. Hence, it is very challenging to design a mobile terminal antenna having an optimal performance in any use case and at any operating frequency by using traditional antenna elements (e.g., PIFA or CCE). Based on the results shown in [I, 15], a part of the hand losses can be avoided by taking the effect of the hand into consideration in antenna design. However, one can always have a grip that will destroy the performance of the antenna. One solution might be to invent new methods to excite the chassis wavemodes in a way that the impact of the user can be minimised regardless of the hand grip, for instance without a traditional antenna element. Thus, a lot of research to build an environment insensitive mobile terminal antenna is still needed.

2.3 Disadvantages of the electromagnetic radiation of the mobile terminals

At the beginning of this chapter, it was discussed how the user can deteriorate the performance of the antenna. Next, the subject is turned around; disadvantages of the electromagnetic radiation of the mobile terminals to a user are discussed. The electromagnetic radiation transmitted by a mobile terminal is discussed with three different points of view: 1) radiation safety aspects, 2) network aspects, and 3) electromagnetic compatibility.



(a) (b)

Fig. 2.6. (a) Absorption of the electromagnetic radiation into the body tissues. (b) Antenna element located close to the user may cause electromagnetic compatibility (EMC) problems on the operation of a hearing-aid device[3].

1) **Radiation safety aspects**: According to the current knowledge, the main influence of electromagnetic radiation (UHF) to human body is the rise in the tissue temperature [1]. For the mobile terminal satisfying the safety margins [1, 48], the temperature rise on the surface of the brain is shown to be not more than $0.2 - 0.3$°C [49]. As a comparison, the normal fluctuation of body temperature is around ±1°C, and in exhausting physical exercise even a temperature rise of 2°C is quite common. However, it has been observed that electromagnetic radiation can accelerate production of cells [50] or it might open a leakage of albumin through the blood-brain barrier (BBB) [51]. Thus, it is very important not to exceed the safety limits of the electromagnetic radiations; rather the exposure should be as small as possible. In order to estimate the influence of the electromagnetic radiation, a measurement standard has been developed: the Specific Absorption Rate (SAR) is a measure of the rate of radio energy absorption in body tissue. The SAR is defined as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg) [1].

[3]Image source: http://www.bigfun.be/Cartoon/Selective+Hearing+Aids.htm

2) **Network aspects**: The interest of the network operators is to optimise the link budget between a base station and a mobile terminal. The optimal link means that the base station can serve as many users as needed with a sufficient quality of services (QoS) [52]. The user of the mobile terminal will reduce the total efficiency of the mobile terminal (as discussed in Sections 2.1 and 2.2) and thus will deteriorate the link quality. To maintain the sufficient QoS, the network will automatically increase the transmit power of the mobile terminal or the base station depending whether the mobile terminal is transmitting or receiving. However, the increased transmit power of the mobile terminal will increase the electromagnetic exposure absorbed by the user and decrease the battery life of the mobile terminal compared to the case with a smaller transmit power. In addition, the deteriorated link quality will decrease the cell size of the network increasing the cost for the operators [53]. Hence, it is very important to take into account the user's hand as well, when designing a handset antenna. For instance with the talking grip, the user's hand absorbs a significant portion of the radiated power and thus causes an increase of transmit power if the link quality is kept unchanged. This will increase the electromagnetic exposure toward user's head [54, 55]. Thus, an antenna with a robust performance with user's hand might have a better real-use-case SAR performance compared to an antenna designed to work best in free space or only with the head.

3) **Electromagnetic compatibility**: As discussed earlier, the mobile handset antenna has to be designed in such a way that it fulfils the safety margins [1, 48] and maximises the transfer of the electromagnetic energy between the base station and the mobile device. In addition, a mobile device used beside the user's ear may cause electromagnetic compatibility (EMC) problems on the operation of a hearing-aid device (see Fig. 2.6) and thus the handset antenna should also fulfil the hearing-aid compatibility[4] (HAC) [56]. These are the problems that an antenna designer have to address. In the next chapter, some new ideas about how to reduce the electromagnetic exposure without sacrificing significantly the link quality, are presented.

[4]In the USA, at least 50% of all marketed mobile handsets have to meet the HAC requirements. Whereas in the EU, the HAC standard is not currently valid

3. Reduction of interaction between a user and a mobile terminal antenna

3.1 Antenna shielding

Traditionally, the antenna element is placed on the backside of the mobile handset, away from the head in the talk position (see Fig. 3.1 (a)). This makes it easier to fulfil the radiation exposure restrictions (SAR limits) and the antenna performance is better in that use position. From the antenna operation point of view, this kind of antenna configuration is far from being optimal in many other use positions. For instance, when using the mobile terminal in the data mode (browsing position), the user's fingers may cover the antenna element (see Fig. 3.1 (b)), reducing the radiation efficiency and causing frequency detuning, as discussed earlier. To solve the above-mentioned issues, an effective antenna shielding method to decrease the effect of the hand and head on the operation of mobile terminal antennas is discussed in this section. The antenna shielding concept is introduced in [II] and the operation is verified by measurements in [III].

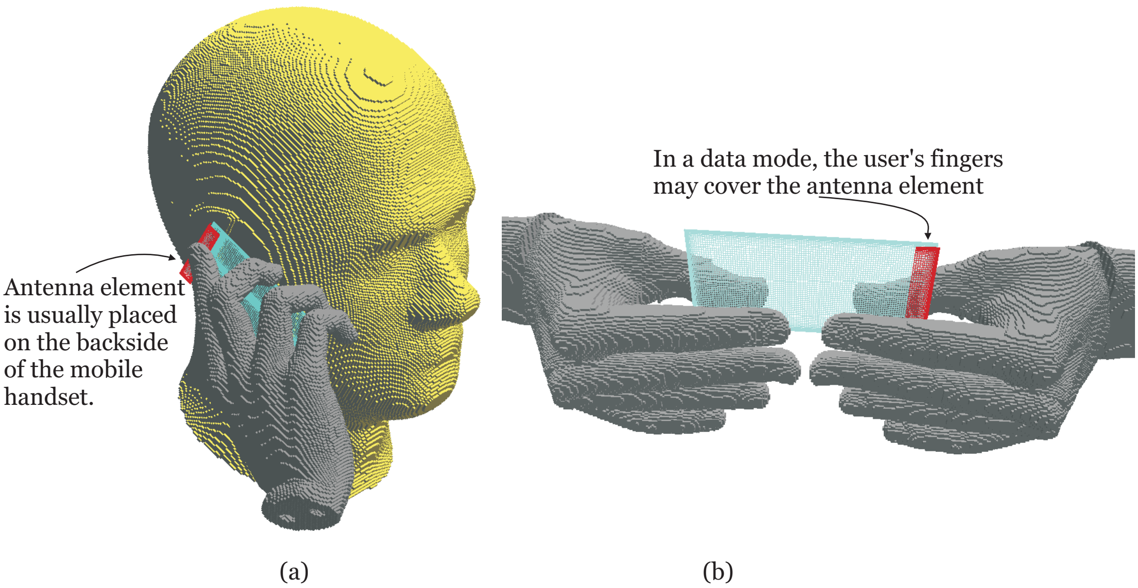


Fig. 3.1. Typical placement of the mobile terminal antenna, (a) in talking position, and (b)in browsing position.

The proposed shielded antenna structure (see Fig. 3.2) consists of two non-self resonant capacitive coupling element (CCE) antennas [14]. Here, an active antenna element refers to the case where the antenna element is switched on (feed connected) and a passive element refers to the case where the antenna element is switched off (floating or connected to the ground, see Figs. 3.2 a and b). The operational principle of the shielded structure is such that one antenna element is active at a time and the other is passive. If the passive element is not connected to the ground (see Fig. 3.2 a), the antenna structure can be treated as an off-ground structure[1]. If the passive element is connected to the ground (see Fig. 3.2 b), it can be considered as an extension of the ground plane to improve the shielding effect from electromagnetic exposure. The simplest and a cost efficient way to implement the selection of the antenna element is to utilize the information of the current operating mode (talking/browsing). If the talking mode is used (terminal beside the head), the antenna element placed on the back side of the mobile terminal is selected (see Fig. 3.2 c), and the passive antenna element is operating as a shield on the side of the head of the terminal. When the head is not beside the terminal, the antenna element placed on the front face of the terminal is active (see Fig. 3.2 b).

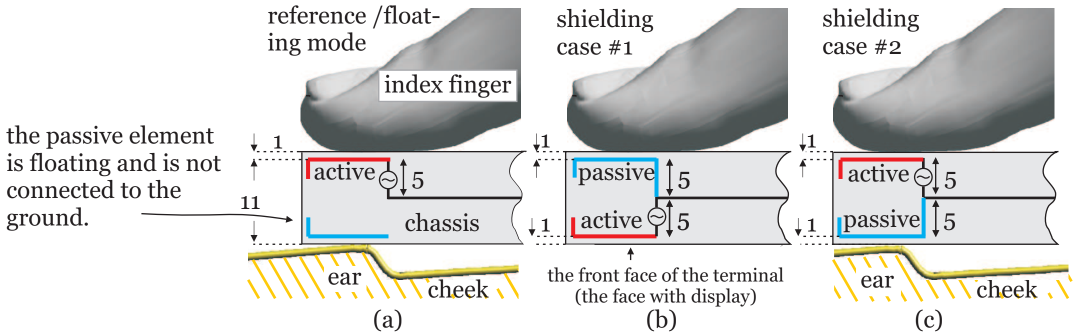


Fig. 3.2. Antenna structure having active and passive antenna elements. (a) reference structure or the case having floating passive antenna element, (b) shielding case #1, and (c) shielding case #2. Dimensions are in millimetres.

In order to verify the promising numerical results introduced in [II], two prototype antennas were built and measured (shielded and reference antennas (see Fig. 3.3)). The operation is demonstrated at the 860-960 MHz and 1590-2500 MHz frequency bands. The input impedance measurements were performed with a VNA in an anechoic chamber. The measured and simulated reflection coefficients (S_{11}) of the shielded and reference antennas at 500-2900 MHz in free space are presented in Fig. 3.4. It can be seen that the measured results match with the simulation results very

[1]Since the passive element has a self-resonance at 1660 MHz (see Fig. 3.4 (a)), the effect of the floating element can be ignored at 900 MHz. At 2000 MHz, the effect of the floating element is still almost non-existence

well.

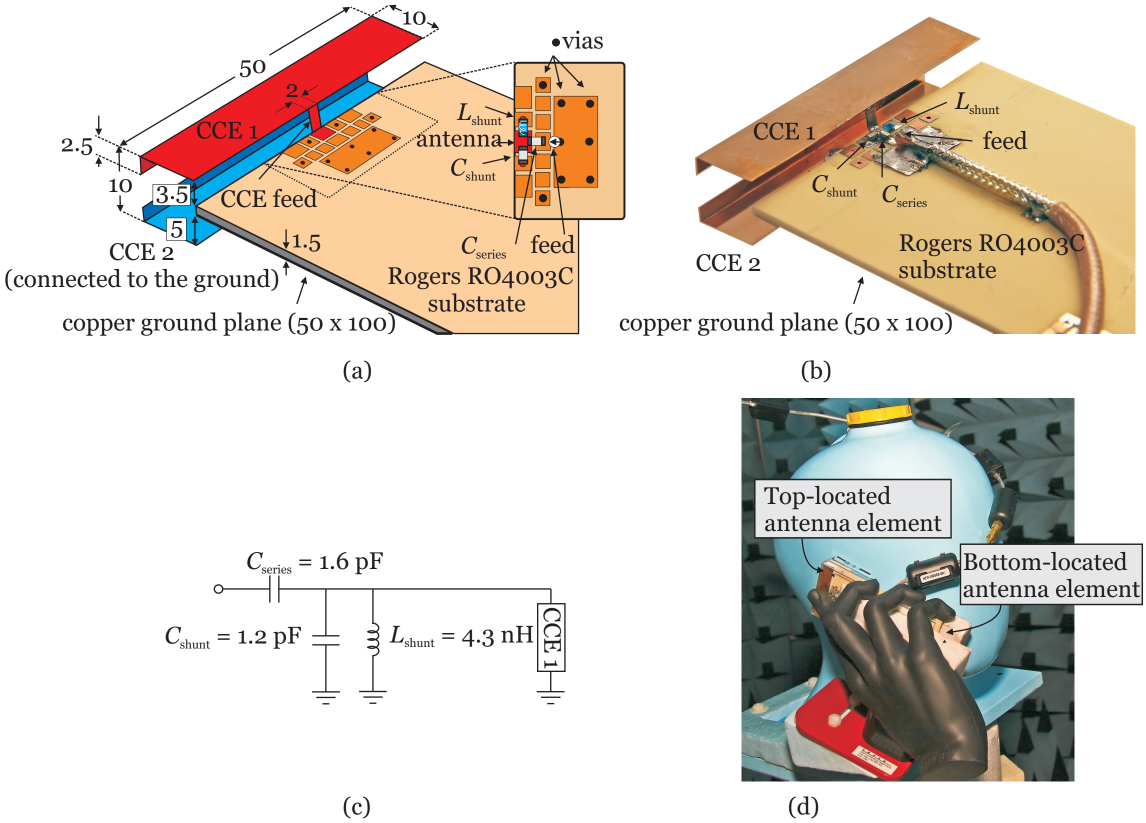
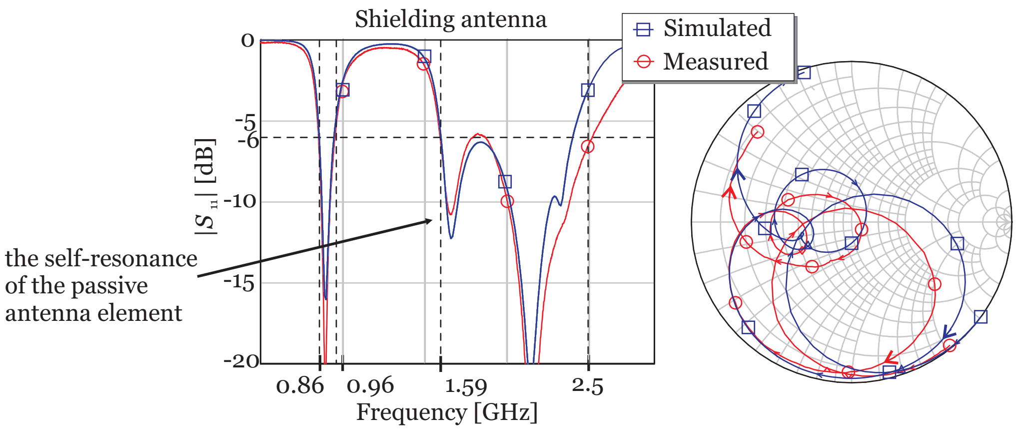


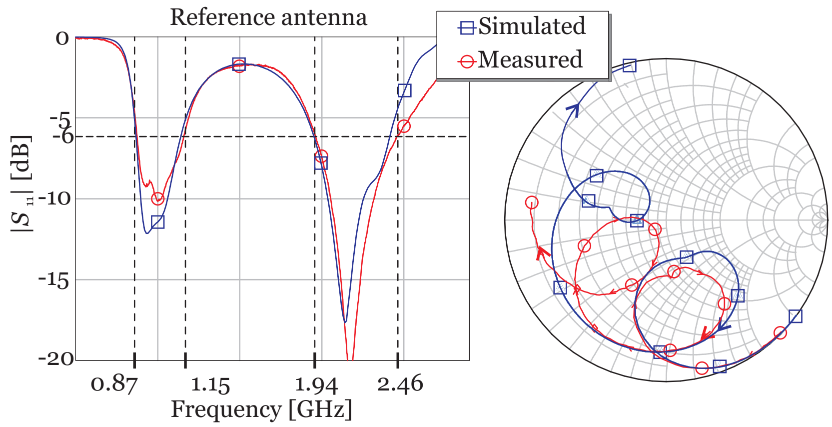
Fig. 3.3. (a) Schematic view of the shielded antenna structure, (b) Fabricated shielded antenna prototype, (c) Schematic view of the matching circuit used in the antenna structures, and (d) measurement set-up in RAMS including the phantom hand SHO V2RB and the generic SAM head filled with tissue-equivalent liquid. Dimensions are in millimetres.

The total efficiency measurements were performed in the Rapid Antenna Measurement System (RAMS) facility of Aalto University [57]. The input impedance and the total efficiency (η_{tot}) of the shielded and reference antennas were measured in free space and with the hand and head phantoms. The matching efficiency (η_{m}) can be calculated from the $|S_{11}|$ as follows: $\eta_{\mathrm{m}} = 1 - |S_{11}|^2$. The η_{tot} is the product of the radiation efficiency (η_{rad}) and the η_{m}. Thus, the η_{rad} can be calculated by using the equation: $\eta_{\mathrm{rad}} = \eta_{\mathrm{tot}}/\eta_{\mathrm{m}}$. The simulated and measured radiation efficiencies (see Fig. 3.5) indicate a good agreement. The maximum difference between the measured and simulated radiation efficiencies is less than 1 dB (see Fig. 3.5). The radiation efficiencies were calculated based on the free space dissipative losses of the matching circuitry. However, the dissipative losses of the matching circuit depend slightly on the effect of the user on the antenna input impedance [58].

The results shown in Table 3.1 indicate that the shielded antenna structure has two specific operating modes at 900 MHz: In *case#1 top*, the η_{rad} with the hand can be improved by 2.2 dB compared to the reference structure, and in *case#2 top* the η_{rad}



(a)



(b)

Fig. 3.4. Simulated and measured S-parameters of (a) the proposed structure, and (b) the reference structure in free space.

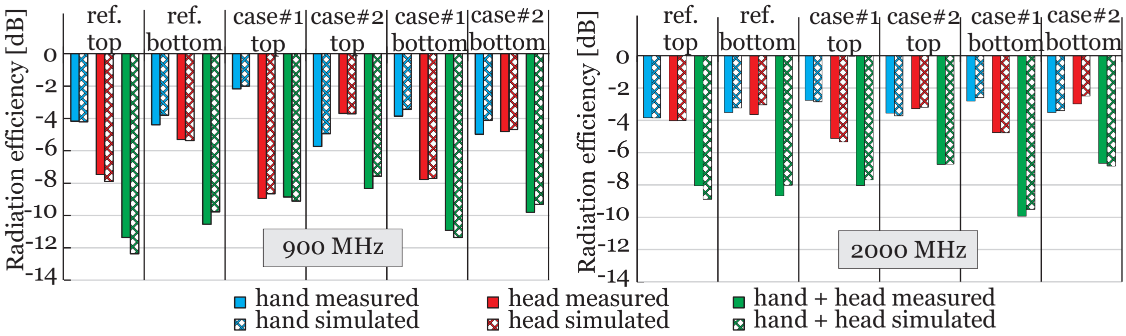
Table 3.1. Improvement of radiation and total efficiencies and change of SAR values in hand and head compared to the reference antenna. Green and bold values refer to cases with improvement compared to the reference.

		$\Delta\eta_{rad}$ [dB]			$\Delta\eta_{tot}$ [dB]			ΔSAR [%]		
Freq.	Structure	hand	head	hand+head	hand	head	hand+head	hand	head	head+hand
MHz	case #	simu. / meas.	simu. / meas.	simu. / meas.	simu. / meas.	simu. / meas.	simu. / meas.	simu.	simu.	simu.
900	#1 top	**2.2 / 2.0**	-0.8 / -1.5	**3.3 / 2.5**	**2.9 / 3.0**	-2.8 / -3.4	**2.6 / 1.8**	**-45**	+8	+40
900	#2 top	-0.7 / -1.6	**4.2 / 3.8**	**4.8 / 3.0**	**0.1** / -0.7	**1.8 / 1.9**	**5.0 / 3.3**	+19	**-50**	**-81**
900	#1 bottom	**0.4 / 0.5**	-2.3 / -2.5	-1.6 / -0.4	**0.9 / 1.8**	-2.2 / -2.3	-1.4 / **1.0**	**-16**	+24	+29
900	#2 bottom	-0.3 / -0.6	**0.7 / 0.5**	**0.5 / 0.7**	**0.2 / 0.7**	**0.6 / 1.0**	**0.7 / 2.3**	**-0.4**	**-20**	**-18**
2000	#1 top	**1.0 / 1.1**	-1.3 / -1.1	**1.2** / 0.0	**0.9 / 1.5**	-1.1 / -0.8	**1.2 / 0.4**	**-53**	+14	+31
2000	#2 top	**0.1 / 0.3**	**0.8 / 0.7**	**2.2 / 1.3**	**0.4 / 0.8**	**0.6 / 0.6**	**2.1 / 1.6**	**-32**	**-49**	**-43**
2000	#1 bottom	**0.6 / 0.7**	-1.7 / -1.1	-1.5 / -1.3	**0.7 / 1.0**	-1.5 / **0.1**	-1.5 / -1.3	**-37**	+74	+94
2000	#2 bottom	-0.2 / 0.0	**0.5 / 0.7**	**1.2 / 2.0**	0.0 / **0.1**	**0.7 / 1.8**	**1.3 / 2.2**	**-12**	**-26**	**-38**

The SAR of underlined tissues are considered.

The studied user effect cases are: (hand) the hand only, (head) the head only, and (hand+head) both the hand and head are present.

with the hand and head can be improved by 4.8 dB compared to the reference. In addition, the top-located shielded structure in *case#2 top* outperforms the better performing bottom-located reference with over 2 dB. The benefit of the shielded antenna structure is clearly larger when the antenna elements are top-located. The shielded top-located antenna structures outperform the widely used bottom-located antennas with a large margin.



(a) (b)

Fig. 3.5. Simulated and measured radiation efficiencies (a) at 900 MHz, and (b) at 2000 MHz.

At 2000 MHz, the improvements are not as significant as at 900 MHz. The improvement in the η_{rad} with the hand is 1 dB and with the hand and head 2.2 dB. This is mainly due to the fact that the passive antenna element has a self-resonance at 1660 MHz (see Fig. 3.4 (a)) and thus the passive element is not anymore as good extension of the ground plane as at 900 MHz. The shielding effect is improved at higher frequencies by connecting the passive element to the chassis with multiple connections. However, this approach will lead to an increased complexity and the benefit will be partly or totally lost. Another method to avoid the deteriorated performance at higher frequencies is to shift the self-resonance of the CCE to higher or lower frequencies. This can be done, for instance, by changing the dimensions of the CCE. However, this will lead to a deteriorated shielding performance or narrower bandwidth at lower frequencies if a larger or smaller CCE is used, respectively.

A significant improvement in the hand and head SARs can be seen with the shielded antenna structure compared to the reference structure. For instance, the shielding structure can decrease the SAR in the hand by 45% at 900 MHz, when the index finger is covering the antenna element. Moreover, the head SAR can be decreased by 81% at 900 MHz with hand and head, when the antenna is top-located. At 2000 MHz, the improvements in SAR values are smaller but still about 30 - 50% improvements in the hand and head SARs can be achieved. It is good to note that the improvement of the SAR and the improvement of the total efficiency come together, as could be expected. In [59], it was noticed that the hand SAR (5.2 W/kg) exceeds the SAR exposure limits (4 W/kg) at 836 MHz when the index finger was covering the antenna element of the reference structure (the same antenna structure as in Fig. 3.2 (a)).

The shielding structure could decrease the SAR in the hand by 73% at 836 MHz, when the index finger is covering the antenna element.

With the hand, the main part of the improved η_{tot} and η_m results from the enlarged distance between the index and the active antenna element. The passive antenna element as a shield helps to decrease the hand absorption only by 0.2 dB [II]. On the contrary, the improvement in SAR is mainly due to the shielding effect of the passive antenna element.

The reference structure used in this study was of the off-ground-type and thus it has naturally larger SARs compared to the on-ground-type antennas. In [II], the used reference was of the on-ground-type and the improvements in the η_{rad} with hand, head, and hand+head were 3.6, 2.8, 1.9 dB, respectively at 900 MHz. The improvement in head SAR was about 44%. Hence, the shielded antenna structure outperforms also the on-ground-type reference antenna. In the hand-only case it is useful to have the passive element floating (see Fig. 3.2 a), providing better bandwidth around 900 MHz. However, it is not beneficial to use the floating element with the head since the shielding effect is lost and the SAR is increased.

The shielding structure requires in practice a switching system, which was not implemented in this study. If the implementation losses, approximately 1 dB with current technology [60], were added to the results, the shielded structure would still perform much better compared to the reference. In addition, a semiconductor component like a transistor switch will bring out the problem of distortion of the switching system [61]. The drawbacks of the shielded antenna structure are the increased complexity and the larger volume of the antenna. The future and ongoing work includes the development of the concept to be more suitable in real mobile terminals. For instance, the operation of the antenna element, when located close to the display, will be studied.

3.2 Balanced antenna structures of mobile terminals

The idea of using balanced antenna structures in mobile terminals originates from the fact that a balanced antenna can be electrically isolated from the mobile terminal chassis, unlike a typical unbalanced handset antenna. Especially at the lower UHF-frequencies (below 1 GHz), a significant portion of the power of a traditional handset antenna is originated from the chassis (see Fig. 3.6 (a)). In these structures the effect of the user is significant, changing the matching and decreasing the radiation efficiency regardless if the antenna element itself is covered by the lossy tissue or not, as discussed in Chapter 2. Hence, the use of a balanced antenna structure might be reasonable keeping in mind that the chassis is then not used on purpose as a radiator and thus the antenna is isolated from the chassis (see Fig. 3.6 (b)). The level of the isolation describes the ability of the balanced antenna to reject the electromagnetic coupling to the wavemodes of the chassis. This depends strongly on the used antenna structure, frequency, and the relative location of the antenna and the chassis [IV, 62]. Typically, the closer the balanced antenna is to the chassis, the narrower is the impedance bandwidth (see Fig. 3.7) [IV, 62]. This is mainly due to the increased mirror image effect caused by the chassis that rejects the radiation of the balanced antenna. The worst case is obtained when the balanced antenna is located above the chassis.

3.2.1 Feasibility of balanced antenna structures in mobile terminals

The aim of the study made in [IV] was to investigate the feasibility of balanced antennas in the mobile terminal environment. The characteristics under interest are the following: *a*) the EM isolation between the antenna element and the chassis, *b*) the bandwidth potential of the balanced antenna close to the chassis, and *c*) the interaction between the user and the antenna. The most promising balanced structure seems to be a small bow-tie antenna (see Fig 3.6 (b)) having the self-resonance at 2.7 GHz [IV,62]. At lower frequencies (below the self-resonance), an additional matching circuit is needed. The benefits of using the balanced antenna below the self-resonance are that the coupling to the chassis is quite weak, and that the antenna element is small in size. Another approach to isolate the antenna from the chassis would be to use folded-dipole-type antennas discussed in [63–66]. Those antennas have typically different radiating modes depending on the frequency and thus the balanced mode is achieved only in a certain band (in those cases around 1.8 - 2 GHz). Here, the focus is on the characteristics of the small bow-tie.

As discussed earlier, the utilisation of the chassis currents enlarges the effective antenna size and therefore the balanced antenna structures have to be made larger than traditional antenna elements, such as the PIFA, in order to have the same bandwidth. To keep the size of the antenna small enough to fit inside a mobile terminal one has to allow a narrower instantaneous impedance bandwidth (2-3%) (see Fig. 3.7) for the balanced antenna as compared to the traditional elements, and tune the frequency [60, 67–69], or use a traditional antenna element at the lower UHF-frequencies, below 1 GHz. The required frequency tuning at lower frequencies will cause extra loss introduced by, for instance, a switching/tuning system. Secondly,

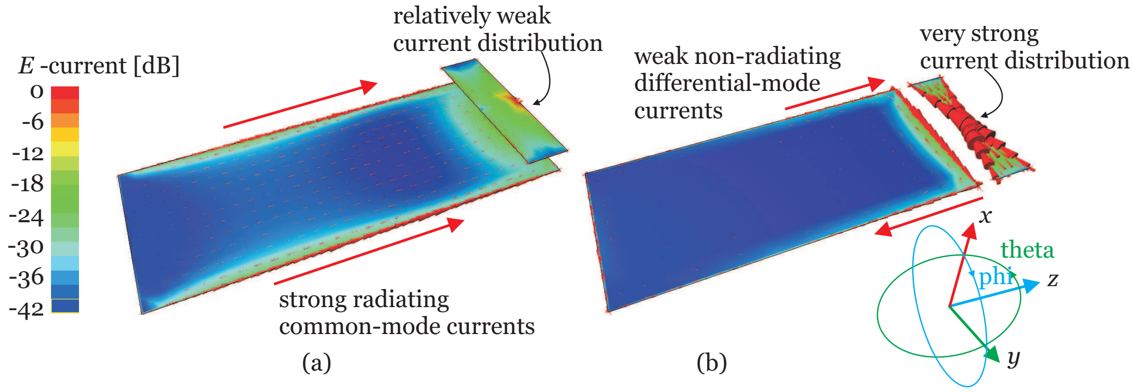


Fig. 3.6. Simulated current distributions of the (a) CCE structure, and (b) bow-tie structure at 1800 MHz. The maximum E-current is 10 A/m.

it is very challenging to desing a tuning system for an antenna having very high quality factor (bow-tie, etc.). In addition, a semiconductor component like a transistor switch will bring out the problem of distortion of the frequency tuning circuit [61]. These problems can be reduced by using RF microelectromechanical systems (MEMS) switches. RF MEMS switches have some overwhelming advantages over traditional pin diodes and GaAs FETs [70, 71]. They can be used to build RF circuits with very low power consumption, resistance, and capacitance. The drawbacks of the current technology are limited lifetime, high development costs, and lack of general availability.

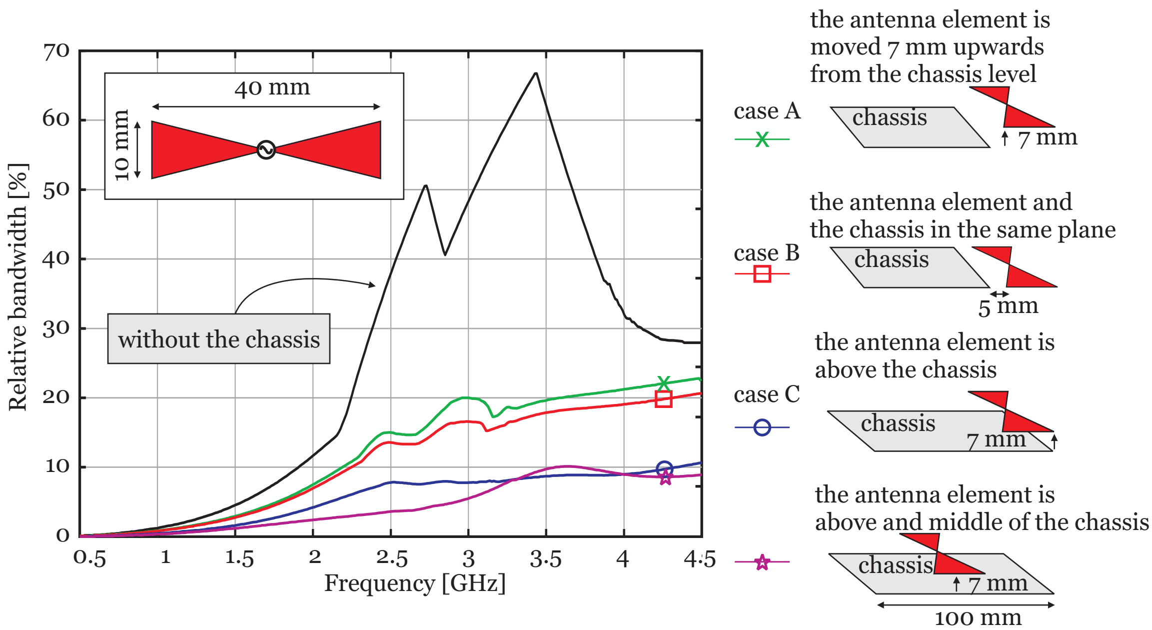


Fig. 3.7. Achievable bandwidth potentials of a small bow-tie element in different antenna positions. The bandwidths are calculated by using the matching criterion of the optimal overcoupling [72]. In all cases the total length of the structure is 100 mm.

A rough estimate of the main benefits and drawbacks of the balanced antennas can be seen in Fig. 3.6. The bow-tie is fairly well isolated from the chassis, which can be seen from the weak differential currents along the long edges of the chassis. Conversely, the bow-tie has much stronger electric fields close to the antenna element compared to the traditional CCE antenna (see Figs. 3.11 and 3.12). This will cause problems when lossy tissue is located close to the antenna. In [IV], the performance of balanced antenna structures with a user was compared to the traditional antenna (denoted as CCE reference in Table 3.2). Two different positions for the bow-tie antenna element are used: in *case A* the antenna element is moved 7 mm upwards from the chassis, and in *case B* the antenna element and the chassis are located in the same plane (see Fig. 3.8).

Several observations (a-e) can be made based on the results in Table 3.2:

a) The small bow-tie is quite robust to the distance between the index finger and the antenna element in terms of the frequency shift.

b) If we compare the frequency shift (Δf_r) results to the reference antenna we see that the balanced bow-tie performs especially well at the 900-MHz frequency range but at the higher frequencies (1800 MHz) the advantage is almost lost, especially if the antenna element is bottom located.

c) The balanced bow-tie performs best when the antenna element is top-located. When the antenna element is bottom-located, the palm decreases the resonant frequency and absorbs more power than in the top-located case.

d) When comparing the radiation efficiencies with hand or head it can be seen that the distance between the antenna element and the tissue (hand or head) have a huge impact on the antenna performance; the closer the bow-tie is to the tissue, the lower is the radiation efficiency and the higher is the SAR. It is interesting to observe that the radiation efficiencies of the reference antenna are practically the same with bottom- and top-located cases at 900 MHz. This is mainly due to the fact that the chassis is the main radiator at lower frequencies, as discussed earlier.

e) The SAR is very high (exceeds clearly the safety limits) for the bow-tie structure when the antenna element is close to the head in *case B*. One can also see that when moving the antenna structure 7 mm further in *case A* it is possible to decrease the SAR by 30% at 900 MHz and by 60% at 1800 MHz. Hence, the SAR results are in line with the results of the shielded antennas; it is very beneficial for antenna performance to increase the distance between the radiator and the lossy tissue. The SARs were studied with the bottom-located cases and are supposed to be a little higher when the antenna elements are top-located [III]. The SAR performance of the bow-tie can be improved by using an EM shield at a cost of decreased impedance bandwidth (see Fig. 3.7).

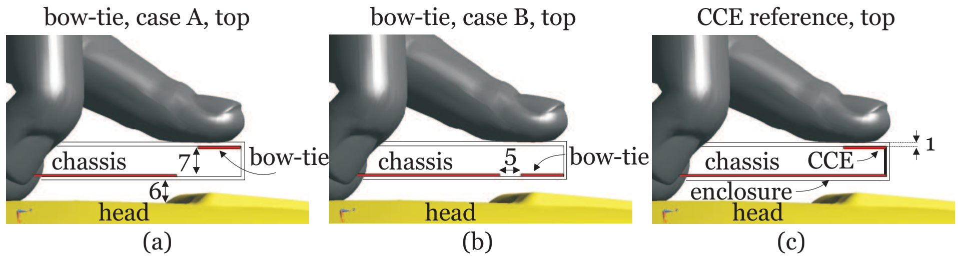


Fig. 3.8. (a) Bow-tie is placed next to index finger, (b) bow-tie is placed at the same plane as the chassis, and (c) CCE is placed next to index finger. All dimensions are in millimetres.

Table 3.2. Effect of the user's hand or head on matching, radiation efficiency, and SAR at 900 MHz and 1800 MHz. Green and bold values refer to cases with improvement compared to the reference.

	900 MHz				1800 MHz			
	with hand		with head		with hand		with head	
Structure	Δf_r [%]	η_{rad} [dB]	SAR [W/kg]	η_{rad} [dB]	Δf_r [%]	η_{rad} [dB]	SAR [W/kg]	η_{rad} [dB]
CCE reference, top	-5.8	-3.4	-	-	-3.6	-4.4	-	-
CCE reference, bottom	-4.1	-3.2	2.4	-5.2	-1.8	-2.8	1.2	-3.3
bow-tie, case A, top	**-1.8**	**-2.8**	-	-	**-1.6**	**-1.7**	-	-
bow-tie, case A, bottom	**-3.2**	-4.9	2.7	**-4.2**	-3.6	-3.2	**0.9**	**-2.1**
bow-tie, case B, top	**-1.7**	**-1.1**	-	-	**-1.7**	**-0.9**	-	-
bow-tie, case B, bottom	**-2.3**	-4.6	3.9	-8.5	-2.4	-2.8	2.2	-4.1

at 900 MHz SAR values are normalized to 0.25 W input power (+24 dBm power class)

at 1800 MHz SAR values are normalized to 0.125 W input power (+21 dBm power class)

SAR is calculated over 10 g of body tissue

3.2.2 Combination of unbalanced and balanced antenna on a single terminal

Recently, the main trend is towards even more and more radio systems each requiring an antenna [2]. In addition, the number of the antennas in mobile terminals will increase due to the increasing usage of multiple-input and multiple-output (MIMO) technology, for instance, in the long term evolution (LTE) systems [73]. However, the space available for the antennas is the same or even decreasing. This will cause, for instance, EM isolation problems. If multiple antenna elements are mounted on the same chassis at lower UHF frequencies (under 1 GHz), there will inevitably be strong mutual coupling between them, since each antenna element has a strong coupling to the common chassis and hence are connected together (the chassis is the main radiator). Thus, the optimised placement of the antenna elements or galvanic isolation will not give significant EM isolation improvement in that frequency band. Different EM isolation techniques have been investigated in many previous publications [74–76]. However, many of EM isolation techniques are based on the resonance phenomenon (the dimensions of the EM isolation structures are normally proportional to $\lambda/4$) and have thus inherently narrow bandwidth. In addition, at the lower UHF frequencies, those kinds of structures would be typically impractically long to be used in mobile terminals. As discussed earlier, one solution for the problem is to use a combination of balanced and unbalanced antennas (see Figs. 3.9 and 3.10 (a)).

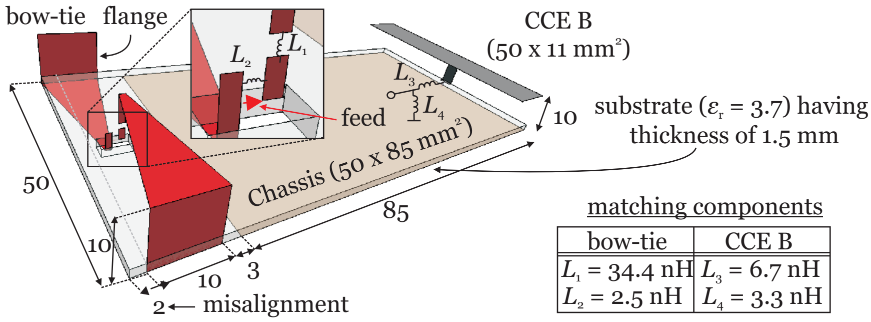


Fig. 3.9. Antenna structure having CCE and bow-tie antennas (BUB). Dimensions are in millimeters.

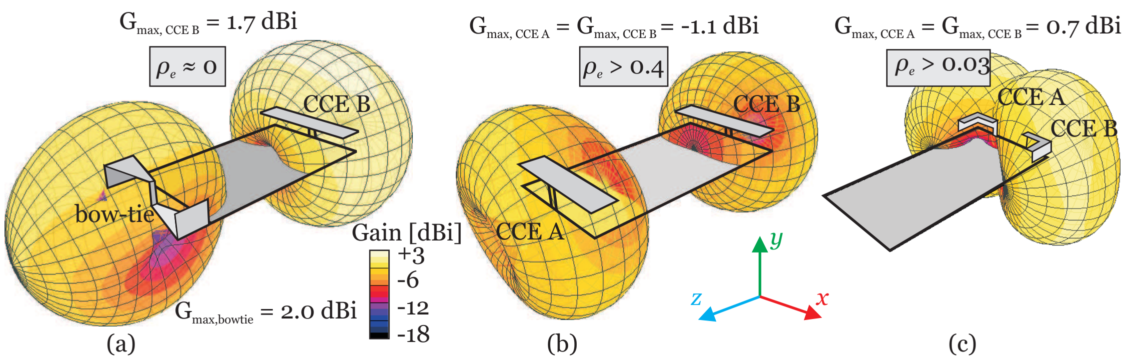


Fig. 3.10. Simulated 3D radiation patterns of (a) the BUB, (b) the reference #1, and (c) the reference #2 structures.

The CCE antenna structure and the bow-tie (see Fig. 3.6) have almost orthogonal dipole-type radiation patterns [IV]. Consequently, the envelope correlation (ρ_e) defined from the 3-D radiation patterns [77], predict a good diversity gain (DG) performance for the combined antenna structure. The bow-tie has also very low cross-polarization indicating extremely low coupling to the chassis wavemode. These two characteristics suggest that a combination of a balanced and an unbalanced antenna (BUB) in a mobile terminal might have a very good DG and EM isolation performance.

The combined balanced and unbalanced (BUB) antenna consists of a bow-tie and CCE antennas located at the opposite ends of the chassis, see Fig. 3.9. The bow-tie consists of two horizontal triangle-shaped antenna elements and vertically oriented flanges. The purpose of the flanges is to increase the impedance bandwidth by filling the available volume more efficiently compared to the flat case. The electromagnetic isolation can be increased about 10 dB compared to the symmetric case by misaligning the bow-tie elements by 2 mm from the centre, see Fig. 3.9. The desired antenna resonances in both antenna elements are achieved by using a lumped-element matching circuit. Two reference cases are investigated to obtain reliable evaluation of the proposed isolated antenna structure (see Fig. 3.10 (a)). Both the references #1 and #2 have two identical antenna elements. In ref. #1 (Fig. 3.10 (b)) the elements are placed at the opposite ends of the chassis and the placement is similar to the BUB structure. In ref. #2 (Fig. 3.10 (c)), two L-shaped antenna elements are placed at the adjacent corners at the same short edge of the chassis.

Table 3.3. Estimated diversity performance of the antennas in different propagation environments at 900 MHz. DG is calculated at the 99% reliability level using the maximal ratio combining (MRC) technique. MEG_1 refers to the bow-tie or CCE A and MEG_2 refers to the CCE B.

Structure	isotropic				urban 1				urban 2			
	ρ_e	MEG_1 [dB]	MEG_2 [dB]	DG / EDG [dB]	ρ_e	MEG_1 [dB]	MEG_2 [dB]	DG / EDG [dB]	ρ_e	MEG_1 [dB]	MEG_2 [dB]	DG / EDG [dB]
Ref. #1	0.406	-6.54	-6.54	10.44 / 7.12	0.787	-9.22	-5.88	6.78 / 3.46	0.817	-6.19	-4.26	7.51 / 4.19
Ref. #2	0.028	-4.70	-4.70	11.44 / 9.89	0.083	-6.41	-3.12	9.69 / 8.14	0.405	-3.88	-3.33	10.16 / 8.61
BUB	0.000	-3.13	-3.19	11.47 / 11.41	0.112	-2.83	-5.69	9.83 / 9.77	0.002	-4.32	-2.25	10.47 / 10.41

Scenario parameters in azimuth plane are uniform.
Scenario parameters in elevation plane are the following (Gaussian) [78]:
-isotropic: XPR = 0 dB, $m_V = m_H = 0°$, $\sigma_V = \sigma_H = \infty$
-urban 1: Tokyo, the Ningyo-cho route: XPR = 5.1 dB, $m_V = 19°$, $\sigma_V = 20°$, $m_H = 32°$, $\sigma_H = 64°$
-urban 2: Tokyo, the Kabuto-cho route: XPR = 6.8 dB, $m_V = 20°$, $\sigma_V = 42°$, $m_H = 50°$, $\sigma_H = 90°$

The results shown in [V] indicate a good EM isolation performance (better than 22 dB port-to-port isolation at 900 MHz) for the bow-tie and CCE combination structure. In addition, the gain patterns in Fig. 3.10 show that the unbalanced (CCE) and balanced (bow-tie) antenna elements have almost orthogonal radiation patterns. This is due to the fact that the antenna structures and thus their 'effective height vectors' are positioned perpendicularly compared to each other and because the balanced structures are well isolated from the chassis. Thus, pattern diversity can be achieved. The diversity performance of the antenna structure can be estimated by calculating the mean effective gain (MEG) [78] and the envelope correlation (ρ_e) [77] of the antenna structures in different radio propagation environments. To achieve a great improvement from a diversity system, it is required to have a low cross-correlation between the individual branches, otherwise deep fades in the branches will occur simultaneously decreasing the DG. Also the mean power available from each antenna branch should be as equal as possible to avoid the deterioration of the signal [79].

When taking into account the total embedded radiation efficiency ($\eta_{\mathrm{rad,i}} = 1 - \sum_{\mathrm{j=1}}^{N} |S_{\mathrm{i,j}}|^2$ [80]) of the studied antenna structures, the effective diversity gain[2] (EDG) of the bow-tie outperforms the reference cases by 1.1 - 6.2 dB margins, depending on the environment and structures under comparison. However, it is good to note that the values in Table 3.3 are calculated at one frequency point (900 MHz) and since the bow-tie is quite narrowband ($\sim$2-3% at the 900-MHz frequency band), the corresponding MEGs are narrowband as well. Therefore, the frequency band where the DG and EDG are valid is limited by the element that has the narrowest impedance bandwidth.

The idea of combining the unbalanced and the balanced antenna can be used to improve the EM isolation between the antennas. In addition, the simulation results show that the proposed structures can achieve a good diversity performance in a real propagation environment and therefore these structures can be used, for example, in MIMO systems to increase the data throughput [81] and the link coverage [82] without an additional frequency bandwidth or transmit power. The drawback is that the achieved impedance bandwidths of the proposed antenna structures are not large enough to cover the requirements of the radio systems in the low UHF-band (LTE700 and LTE800).

Generally, it can be concluded that the balanced antenna structures suite best for upper UHF frequencies, above 2 GHz, where the sufficient bandwidth is easier to achieve and the antenna can be relatively small in size (see Fig. 3.7). In addition, the balanced antennas can be used in the applications that require an excellent electromagnetic isolation between the antennas and to improve the EDG in MIMO systems. Moreover, the balanced antenna structures might also suite well in radio direction finding (RDF) applications where at least three closely packed isolated antenna elements are needed [83].

[2] The effective diversity gain (EDG) is a product of the η_{rad} of the best branch and the DG.

3.3 Near-field control of mobile terminal antennas

Inherent, strong reactive electromagnetic near fields of a mobile terminal may cause problems on the operation of a hearing-aid device. In addition, the exposure of the electromagnetic radiation may exceed the SAR limits and thus the transmit power of the mobile terminal may have to be reduced in order to fulfil the requirements. A typical mobile terminal antenna utilises the chassis of the terminal as a radiator, as discussed earlier in Section 3.2. Therefore, the chassis has a remarkable effect on the near fields of the mobile terminal. The current distribution of the chassis resembles that of a thick dipole [13] and thus the strong electric fields at the ends of the chassis are common (see Figs. 3.11 (a) and (c)). One method to control the near fields would be to modify somehow the chassis geometry. One can, for instance, change the dimensions or the shape of the chassis. However, the display of the mobile device and other design factors set strict restrictions on how to modify the chassis. Actually, the display behaves as a part of the chassis (see Fig. 2.3 (a)) and thus the chassis cannot include significant patterns or cut-offs. In general, the larger are the dimensions of the chassis, the lower are the reactive near fields. Thus, the mobile terminal with large dimensions will have naturally better SAR and HAC performance compared to the terminal with small dimensions [4].

An effective way to control the reactive near fields of the mobile terminals is firstly introduced in [84]. The idea is based on the manipulation of the chassis wavemodes with wavetraps in a way that extended impedance bandwidth can be achieved at higher UHF frequencies (around 2 GHz). The idea was developed further in [VI], where the wavetraps create a high-impedance load on the desired position of the chassis. Thus they modify the chassis wavemode by manipulating the current distributions of the chassis and so the electric and magnetic fields in the opposite end to the antenna element of the chassis are decreased (Fig. 3.11 (b), (d)) by manipulating the current distributions of the chassis. As can be seen in Table 3.4, the wavetraps can reduce the electric and magnetic field values on the HAC plane [VI, 56] by up to 75% and 70%, respectively. It is also seen that the electric field is directed away from the head (from the lower part of the terminal) and thus the SAR can also be decreased in the head by 23% at 1880 MHz compared to the case without the wavetraps [VI].

The disadvantages of the wavetraps are related to the strict requirement of the length of the wavetrap; the length should be the quarter wavelength, and the resonance is typically rather narrow, as can be seen in Fig. 3.13. Moreover, the tissue of the user close to the wavetrap changes the electric length of the wavetrap (as discussed in Section 2.1) hence making the useful operational bandwidth even nar-

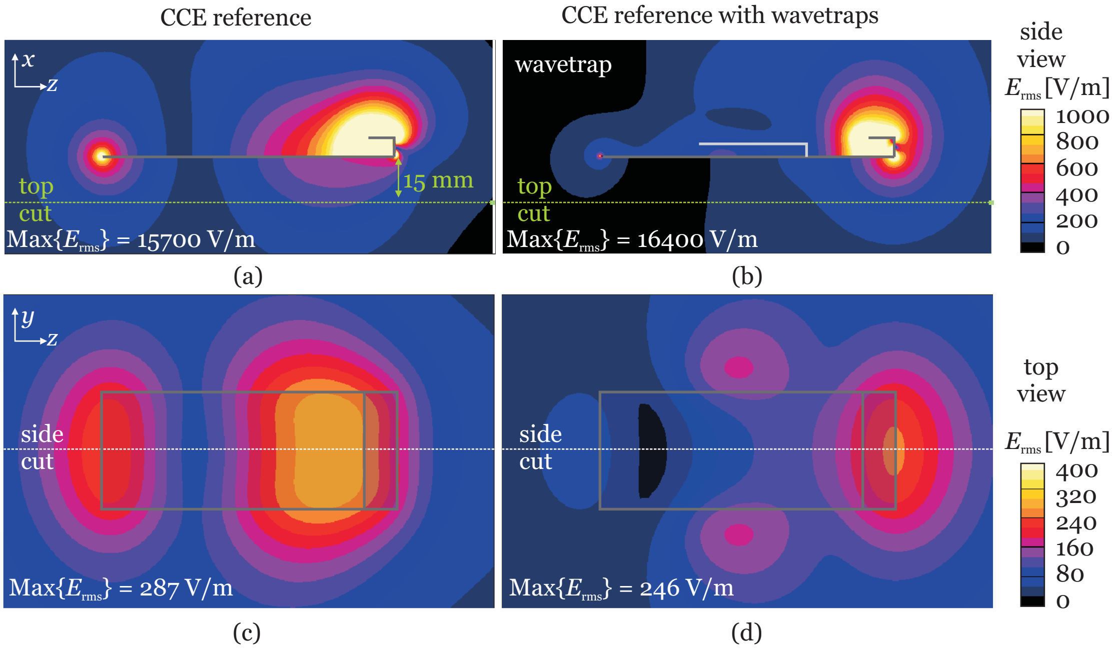


Fig. 3.11. Electric field distributions of the CCE reference, and the CCE reference with wavetraps at 1880 MHz. The side views of the structures are presented in (a) - (b), and the top views are presented in (c) - (d). The field values of the side view are taken from the middle of the terminal (see dotted line of side cut). The field values of the top view are taken at a distance of 15 mm from the chassis (see dotted line of top cut). In all cases, the input power is normalized to 1 W and the mismatch is excluded. The maximum root mean square of the electric field strength (Max$\{E_{rms}\}$) is calculated in each plane.

Table 3.4. Summary of the simulated peak field values on the HAC plane.

Structure	Electric field [V/m]		Magnetic field [A/m]	
(peak field values)	836 MHz	1880 MHz	836 MHz	1880 MHz
reference	551	250	0.67	0.60
reference with wavetraps	-	63	-	0.18
bow-tie, case B	73	73	0.29	0.24
bow-tie with wavetraps, case B	-	26	-	0.09
HAC specification field (peak) limits M3 (AWB = -5 dB)	<266.1	<84.1	<0.80	<0.25
HAC specification field (peak) limits M4 (AWB = -5 dB)	<149.6	<47.3	<0.45	<0.14

at 836 MHz field values are normalized to 2 W (+33 dBm) input power

at 1880 MHz field values are normalized to 1 W (+30 dBm) input power

rower. Multiresonant or tunable wavetraps may increase the operational bandwidth and might improve the operation with a user [85, 86]. In addition, at the lower UHF frequencies, the wavetrap would be impractically long or the achieved operational bandwidth would be too narrow (even with an additional impedance tuning) to be

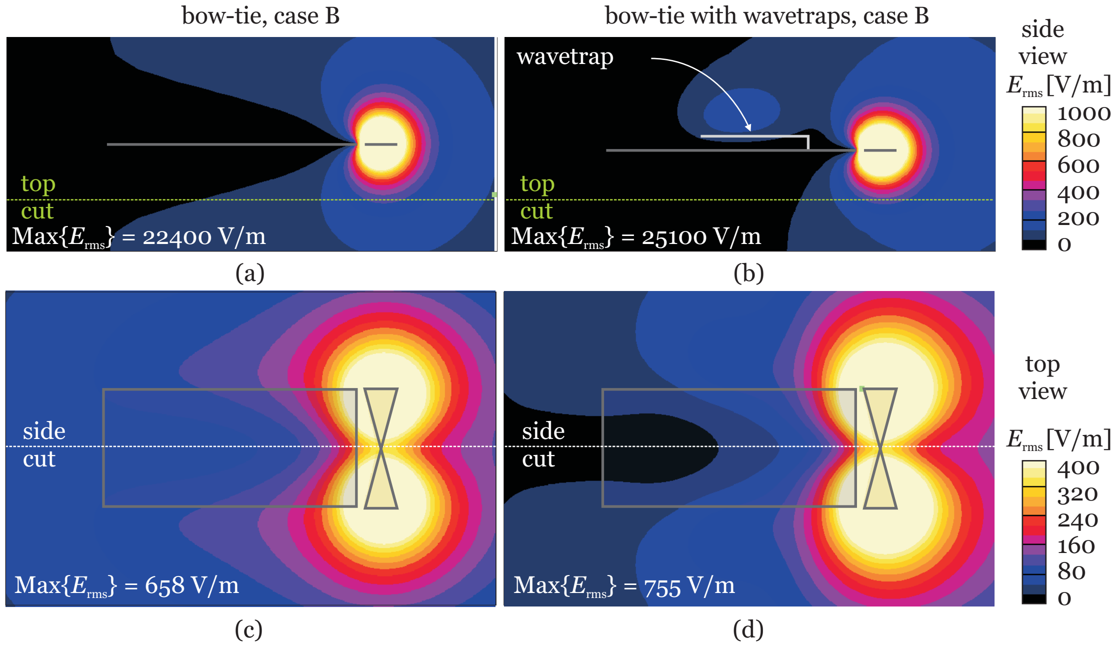


Fig. 3.12. Electric field distributions of the bow-tie antenna without and with wavetraps at 1880 MHz. The side views of the structures are presented in (a) - (b), and the top views are presented in (c) - (d). The field values of the side view are taken from the middle of the terminal (see dotted line of side cut). The field values of the top view are taken at a distance of 15 mm from the chassis (see dotted line of top cut). In all cases, the input power is normalized to 1 W and the mismatch is excluded. The maximum root mean square of the electric field strength (Max$\{E_{rms}\}$) is calculated in each plane.

used in mobile terminals and thus the operation is limited to the higher UHF frequencies (above 1.8 GHz) in practice. In a real handset, the wavetraps will require special arrangement of phone mechanics, for instance, cable outputs cannot be placed under the wavetraps. In addition, the display located close to the wavetrap might deteriorate the performance of the wavetraps.

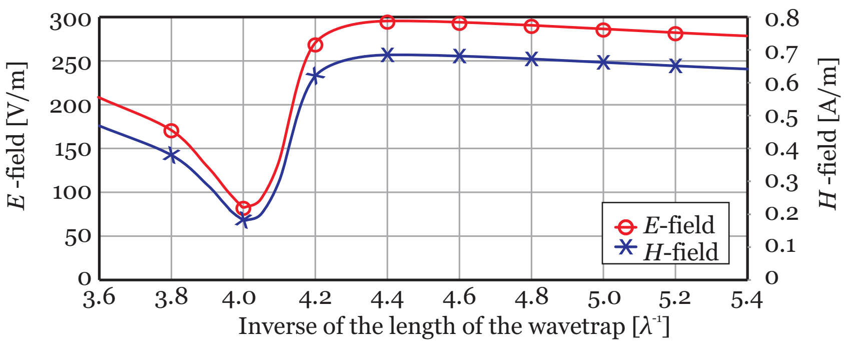


Fig. 3.13. Effect of the length of the wavetrap on the E- and H-fields on the HAC plane at 1880 MHz. The best performance is achieved when the length is $\lambda/4$.

Another way to control the reactive near fields is to use the isolated antenna structures. The chassis can be fully or partly isolated from the antenna element depending on the used technique [IV, 63]. Here, the focus is on the balanced antennas and the bow-tie antenna, discussed in Section 3.2, is used as an example of an isolated antenna. As can be seen in Figs. 3.11 and 3.12, the electric field at the open end of the chassis is decreased considerably compared with the non-isolated antennas (CCE reference). Moreover, the electric field can be decreased even more at the open end of the chassis with the help of the wavetraps. This is done at a cost of increased field values near the antenna element compared with the CCE reference (see Max$\{E_{rms}\}$ values in Figs. 3.11 and 3.12). By contrast, this will increase the SAR values, as discussed earlier. It is seen (in Table 3.4) that the bow-tie antenna can fulfil the tight M3 specification of the HAC standard even without the wavetraps and it is possible to improve even more the HAC performance by using the wavetraps (to fulfil the M4 specification [56]). Probably, the SAR performance can also be slightly improved with the help of the wavetraps since the wavetraps can direct the fields away from the head (see Fig. 3.12 (b) and (d)), as discussed earlier.

As a general conclusion, the modification of the reactive near fields will change the power distributions of the antenna structure and if the radiated power is kept constant, the problem is basically transferred from one place to another (see Fig. 3.11). In the case of the wavetraps, the field is directed upwards from the chassis (away from the head) and thus it is possible to improve both the HAC and the SAR performance at the same time. In the case of the balanced bow-tie, the chassis is not used as a radiator and hence the fields are concentrated near the antenna element. This will lead to an extremely good HAC performance but on the other side the SAR becomes rather high.

4. Conclusions

Electronically robust mobile terminal antennas were studied in this thesis by exposing the antennas to external disturbances, mainly caused by the body of the user of a mobile terminal. The effect of antenna dimensioning and antenna location on the ground plane of the device with the user's hand were studied in in [I] and some new antenna implementations tolerant to the user's presence were introduced [II, III, IV, VI]. In addition to this, an isolation improvement method for dual-element mobile terminal antennas was studied [V].

It was shown in [I], that when broadening the impedance bandwidth by increasing the height or the area of the antenna element, there is only a minor effect on the radiation efficiency. On the contrary, the higher the CCE height or the larger the CCE area is, the larger is the frequency detuning as well, resulting in decreased total efficiency but also in wider impedance bandwidth. As a conclusion, the improvement of one property seems to deteriorate the other and hence, it is challenging to design an antenna for a mobile device having an optimal antenna performance in any use case. In the future, new methods to excite the device chassis wavemodes should be studied in order to minimise the effect of the user regardless of the hand grip. For instance, inductive coupling elements might be more tolerant than CCEs to external dielectric material.

Different methods to reduce the electromagnetic exposure and the interaction between the user and a mobile device were studied in [II,III,IV,VI]. It was shown [II,III] that the shielded antenna structures can improve significantly the SAR performance in the hand and head (the SAR can be decreased even by 80% compared to the traditional antenna). It was also proven that the shielded antenna can improve the radiation efficiency in these cases and consequently the link quality and the battery lifetime are improved as well.

The isolated antenna structures were studied [IV] in order to determine if they can be used to reduce the effect of the user compared to the traditional antenna structures. It was shown that the isolated antenna structures suite best for the higher UHF frequencies (over 1.8 GHz), where the feasible-sized antenna is electrically larger and thus the bandwidth requirements are easier to achieve. In certain cases, the isolated antenna structures are shown to increase the radiation efficiency, the effect of the user on matching is very small, and the SAR performance is improved compared to the traditional antenna structures. In addition, it was shown that a combination of an unbalanced and a balanced antenna elements [V] can be used in the applications requiring an excellent electromagnetic isolation between the antennas and to improve the data throughput in MIMO systems. The drawbacks of the isolated antenna structures are associated with the lower UHF frequencies; a narrow impedance bandwidth and high SAR values are common. Here also the performance of the antenna can be deteriorated substantially if the user's fingers or palm cover the whole antenna structure.

Different methods to control the reactive near-fields of the mobile terminals were studied in [IV, VI]. It was shown [VI] that the quarter-wavelength wavetrap can be used to modify the chassis wavemodes in such a way that the field values in the open end of the chassis can be decreased significantly. It is also shown that since the fields are directed away from the head, the SAR is also improved. Another way to decrease the field values in the open end of the chassis is to use the isolated antenna structures [IV].

This work shows that it is difficult to obtain a huge improvement of the antenna performance with a user by using traditional methods to excite the chassis wavemodes; one can always have a grip that, for instance, covers the antenna element and thus destroys the performance of the antenna. One solution might be to invent new methods to excite the chassis wavemodes in a way that the impact of the user can be minimised regardless of the hand grip. In addition, the shielded antenna structure should be developed further to be more suitable in real mobile devices.

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